X-ray Optics at MSFC

Speaker: Kiranmayee Kilaru

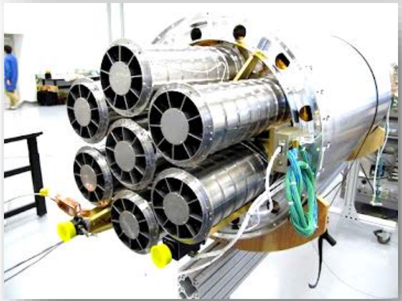
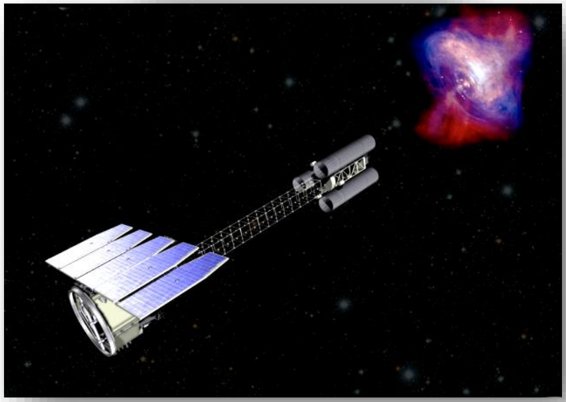
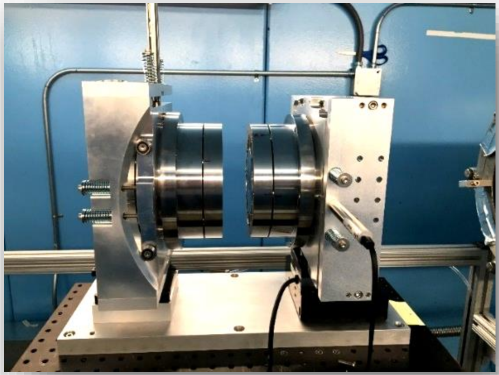
Brian Ramsey & the team of X-ray Astronomy group

NASA Marshall Space Flight Center

X-ray Optics at MSFC

- MSFC has been developing integrated full-shell X-ray optics for ~ 20 years
- Funded through the ROSES/APRA program
- Fabrication Approach: Electroformed nickel replication
- Optics have been built for satellite, rocket and balloon-borne missions and for various spin-off applications



X-ray Optics at MSFC

Optical design and analysis → Fabrication → Metrology

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Coatings → Figure correction → Mounting and alignment

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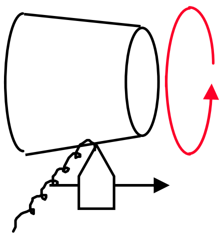
Assembly → X-ray testing

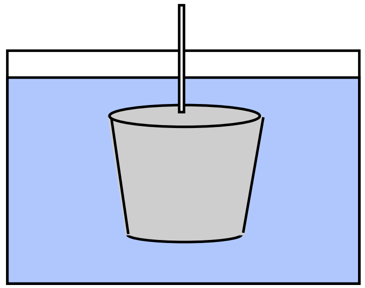
Electroformed Nickel Replication

Mandrel Preparation

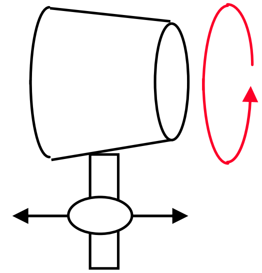
1. CNC machine mandrel from aluminum bar



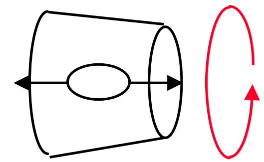
2. Chemical clean and activation & electroless nickel (EN) plate



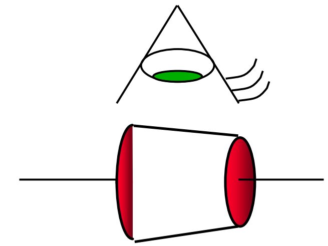
3. Diamond-turn to few 10s nm surface, sub-micron figure accuracy



4.Superpolish to 0.3 – 0.4nm rms finish

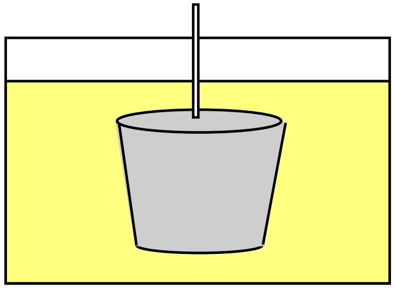


5. Metrology on mandrel

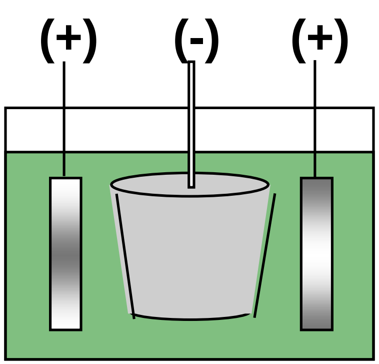


Shell Fabrication

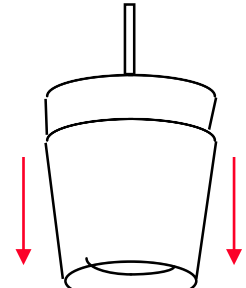
6. Ultrasonic clean and passivation



7. Electroform NiCo shell onto mandrel



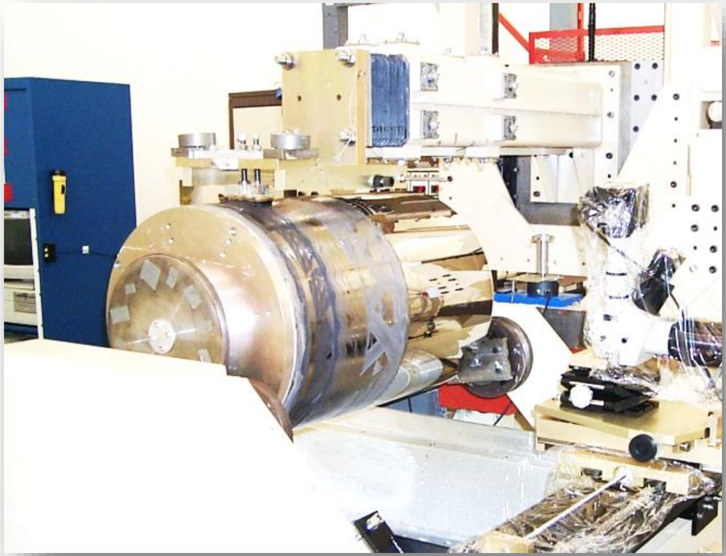
8. Separate optic from mandrel in cold water bath

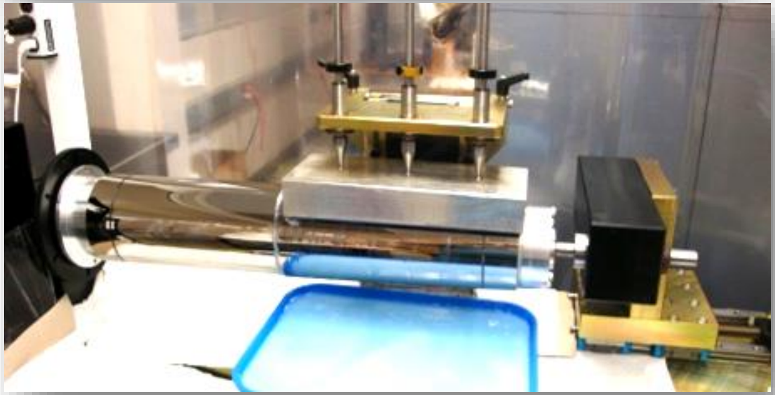


MSFC Infrastructure

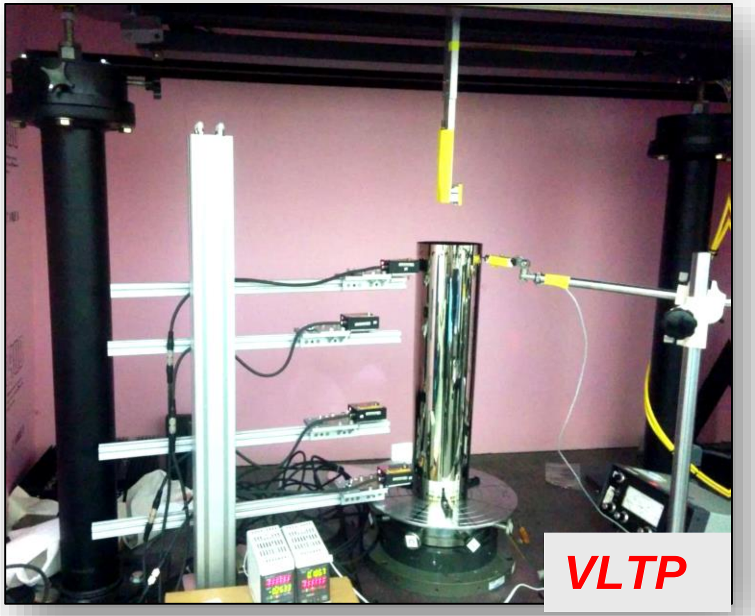
Mandrel Diamond-Turning

Mandrel Polishing



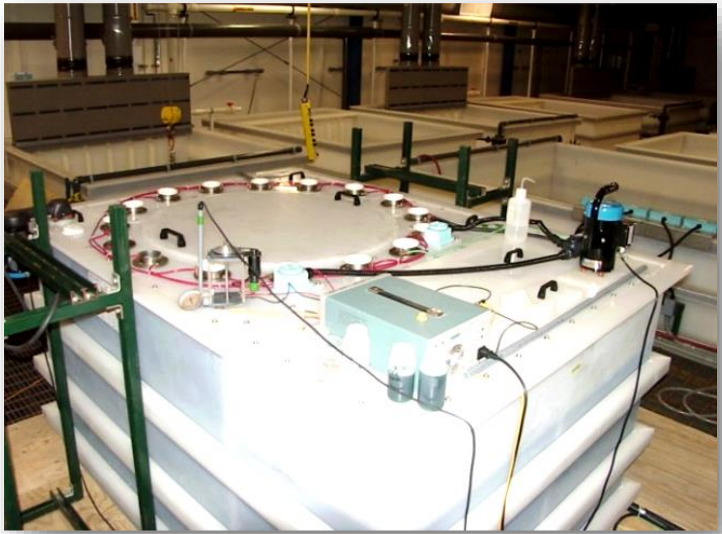


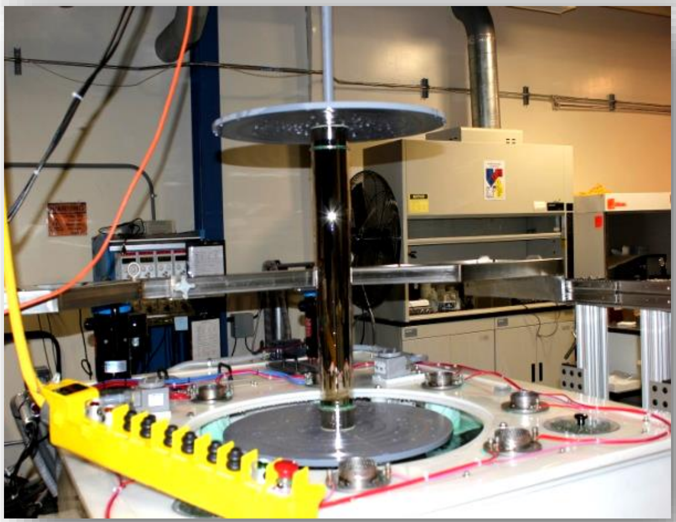
MSFC Infrastructure - Metrology



- Surface profile measurements – Long Trace Profiler, Form Talysurf surface profiler, Zygo interferometer
- Surface roughness measurements - Zygo NewView
- Circularity measurements -Coordinate Measuring Machine
- Coating characterization - XRR (X-ray reflectometer),Step Profiler

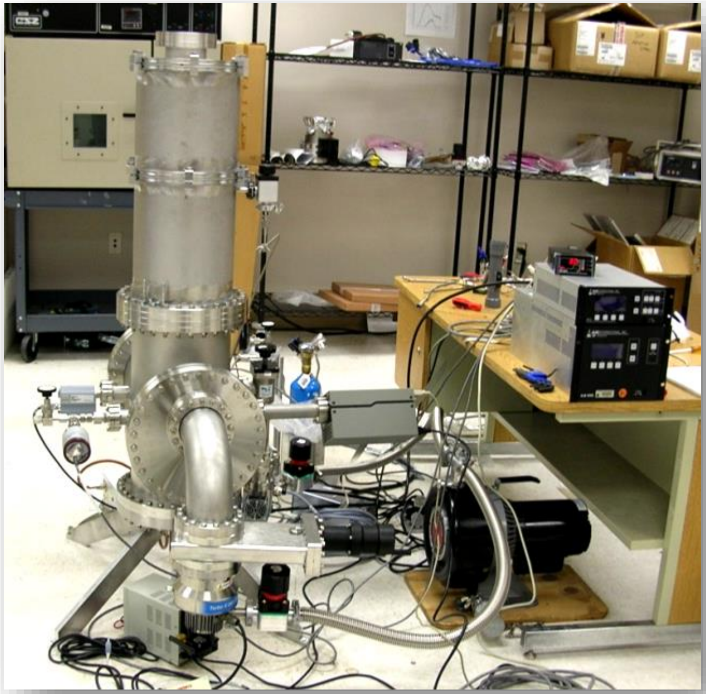
MSFC Infrastructure - Replication





MSFC Infrastructure - Coatings

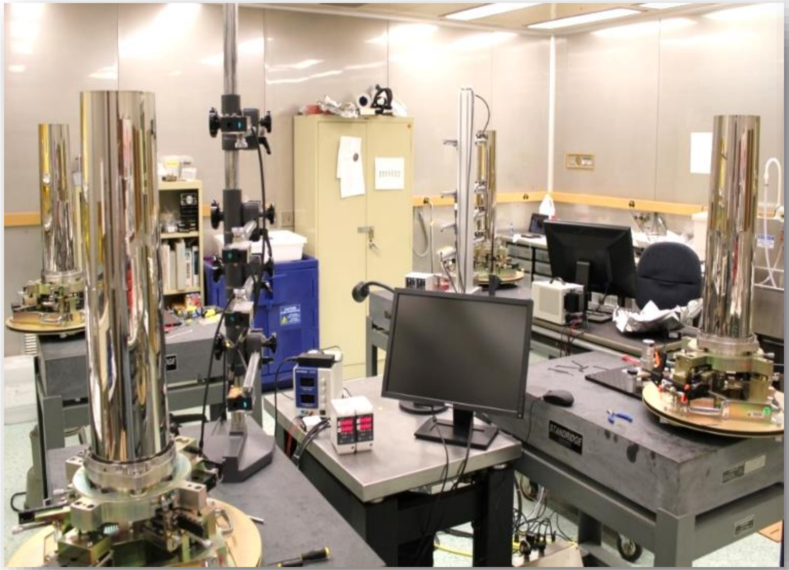
- Custom designed coating chambers for full-shell optics
- RF and DC magnetron sputter deposition
- Underway – Multilayer deposition chamber
- Active research in In-Situ stress measurement and analysis

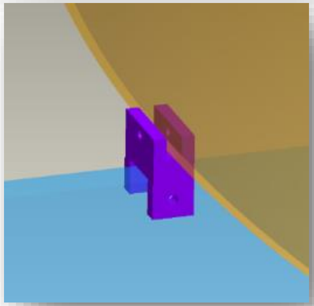


MSFC Infrastructure – Alignment & Assembly

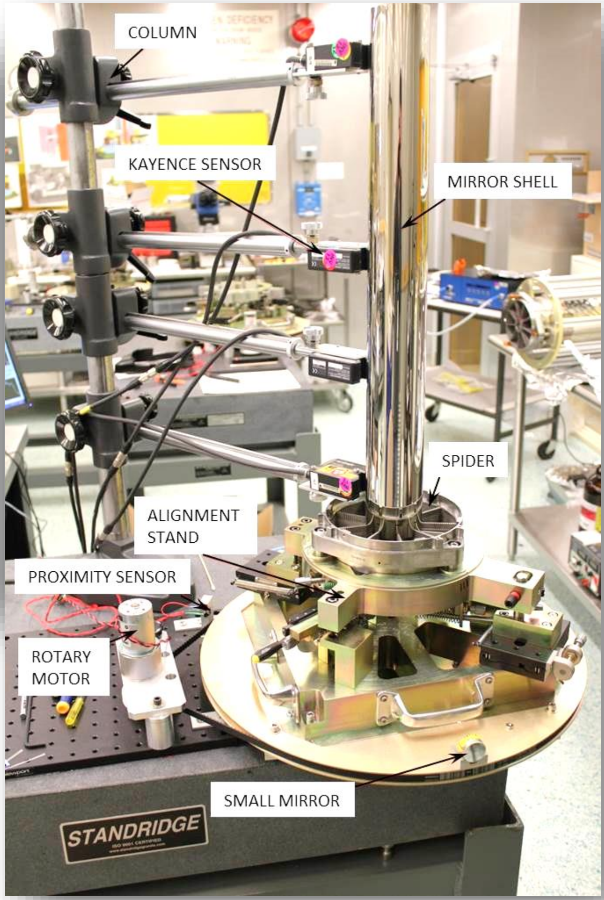
Mirror shell alignment and installation stations

- Shells are glued from one end – less weight for the support system, less obscuration.
- General approach – convert radial displacement into azimuthal one
- The use of the clips (FOXSI – 2007) minimizes the distortions due to epoxy shrinking



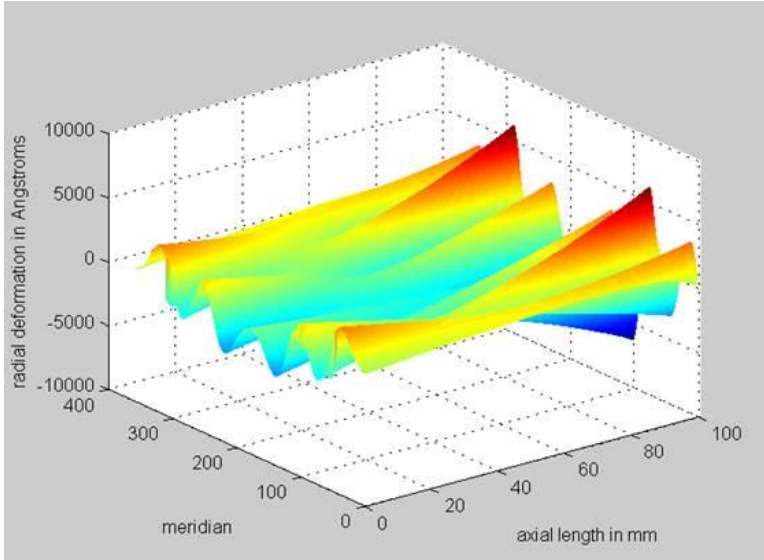


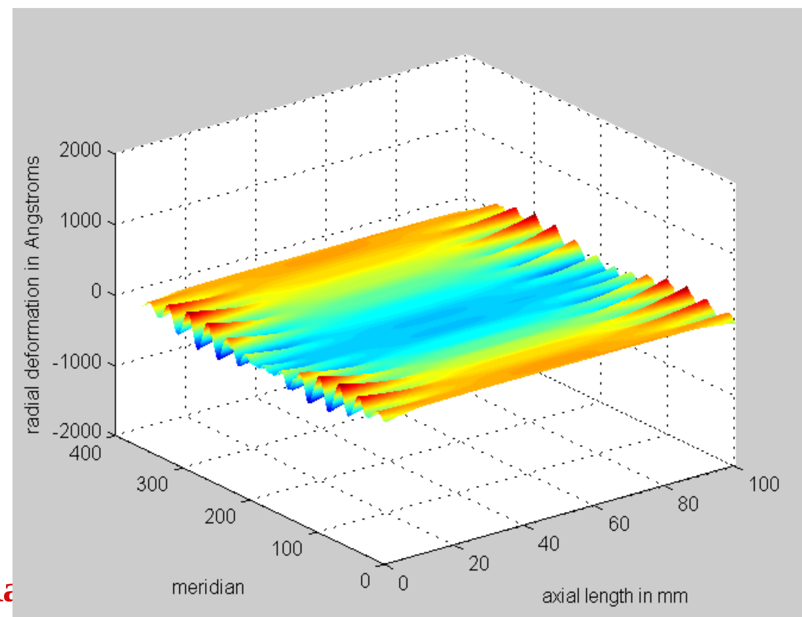
Pre-glued clips minimize the distortions due to epoxy shrinkage



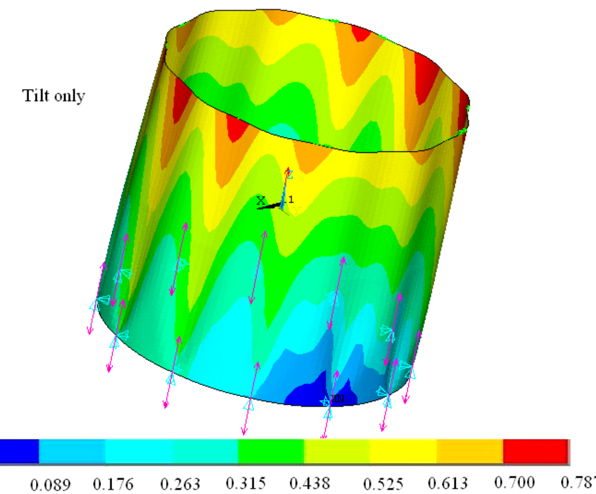
Mikhail Gubarev ; Brian Ramsey ; William Arnold; Alignment system for full-shell replicated x-ray mirrors. Proc. SPIE 7360, EUV and X-Ray Optics: Synergy between Laboratory and Space, 73600A (April 30, 2009); doi:10.1117/12.823848.

Alignment & Assembly - FEA





- Sensitivity to radial displacements
- Any radial distortion on one edge of the shell leads to distortions on other end of the shell

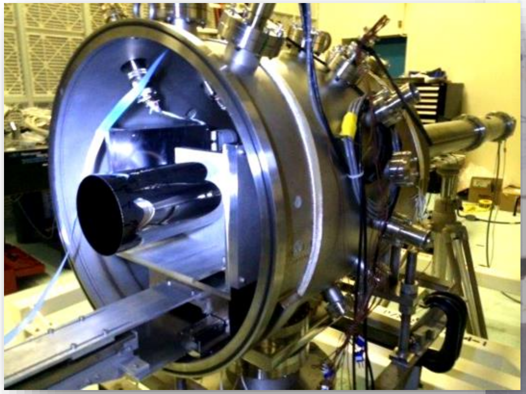


Deformation maps for the 34 cm diameter, 60 cm length monolithic shell supported with 12 points at the bottom of the mirror. The shell is tilted by 1 microradian. The distortion scale is in microns.

MSFC Infrastructure – X-ray Testing

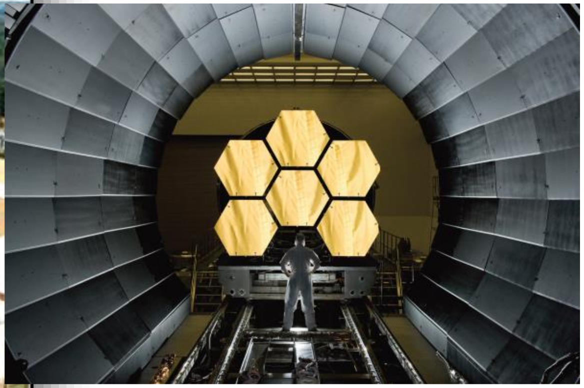
Straylight test facility (SLTF) :

- 100m long vacuum tube
- Clean room facility on either end of the tube
- Can accommodate mirrors upto 1m diameter
- Pumped with cryopumps upto 10^{-7} torr



X-ray and Cryogenic facility (XRCF):

- The XRCF is the world's largest optically clean cryogenic and X-ray test facility.
- The facility consists of a 1,700-foot-long X-ray guide tube, an instrument chamber, and two clean rooms
- In addition to the large vacuum chamber, the facility has a smaller, more cost-effective cryogenic and cryogenic optical testing chamber for subscale testing of smaller instruments

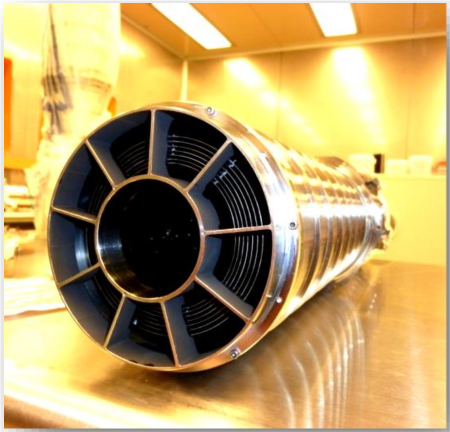


X-Ray Optics Development

Full-shell optics

Down to 50μm thick

Up to 0.5 m diameter



Shells nested into a module

Down to 0.025 m diameter

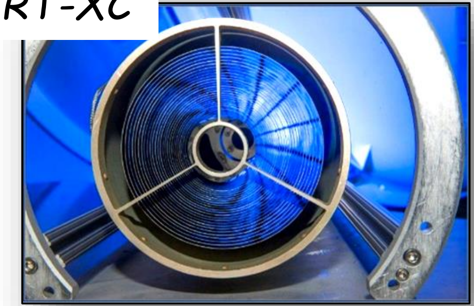
Replicated X-ray optic projects at MSFC

Astronomical applications

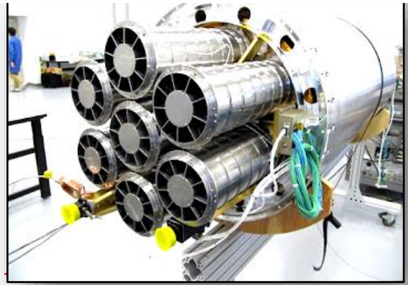
Past

HERO/Super HERO/HEROES

ART-XC

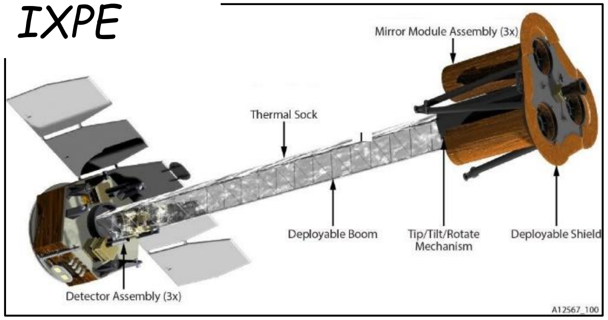


FOXSI/FOXSI-2/FOXSI SMEX

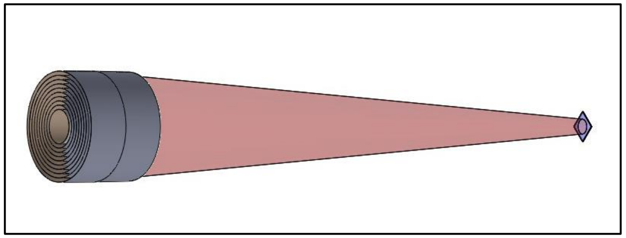


Current

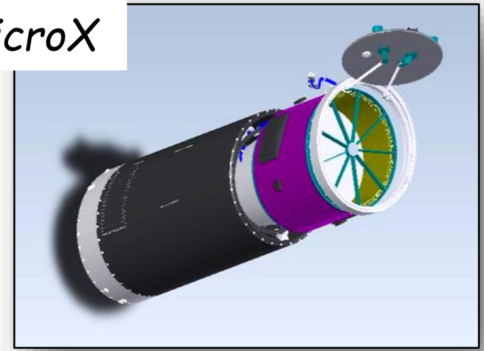
IXPE



MIXO

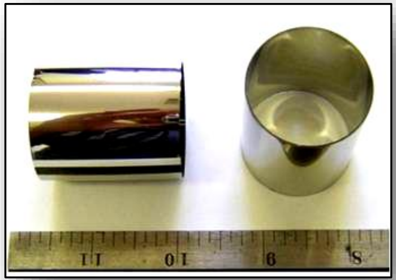


MicroX

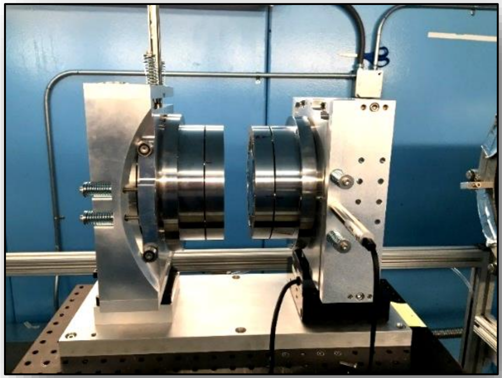


Non-astronomical applications

Medical imaging



Neutron imaging



X-Ray

Replicated X-ray optic projects at MSFC

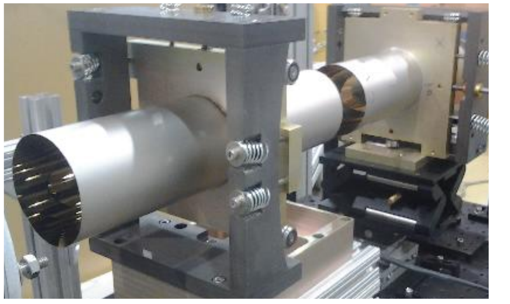
	IXPE	ART-XC	FOXSI	HERO
Energy range (keV)	2 - 10	5 - 30	5 - 15	20 - 70
Optics Effective area	1000 cm^2 at 3 keV	≥ 455 cm^2 at 8 keV	100 cm^2 at 10 keV 10 cm^2 at 15 keV	200 cm^2 at 40 keV, 100 cm^2 at 50 keV
Number of Modules	3	7 (plus 1 spare)	7	8
Focal length (m)	4.0	2.7	2.0	6.0
Number of shells per module	24	28	7	14
Shell diameter range (mm)	162 -272	50 - 150	76 - 103	50 - 94
Coating	-	Ir	Ir	Ir

Spinoff Application: Neutron Microscopy

***Collaboration**: NASA MSFC, NIST, MIT*

- Project aims to build the world’s first neutron microscope
- Re-envisioning and shaping the future of neutron imaging

The microscope will enable:
–Understand targeted drug delivery
–Advance oil and gas recovery
–Perform time resolved SANS measurements during phase transitions (rheology, glass temp., …)
–Enable lithium-air batteries
–Develop additive manufacturing of metal alloys
–Optimize durable, cost effective hydrogen fuel cells
–Reveal solar cell morphologies to reduce the cost of large area solar arrays
–Enhance efficiency of room temp. magnetic refrigeration by imaging 3D magnetic structures
–Improve nutritional value of processed milk by measuring Casein morphology under pressure
–Distinguish internal structure and morphology of graded nanoparticles
–Understand magnetic nanoparticles for hyperthermic cancer treatment, MRI contrast agents



Neutron microscope prototype (2013)
(shells are made from the parabolic segments of existing FOXSI mandrels)

Requirements

- ***10 shell pairs. Parabola-parabola***
- ***1 arc sec FWHM resolution***

Mikhail V. Gubarev ; Boris Khaykovich ; Brian Ramsey ; David Moncton ; Vyacheslav E. Zavlin ; Kiranmayee Kilaru ; Suzanne Romaine ; Richard E. Rosati ; Ricardo Bruni ; Lee Robertson ; Lowell Crow ; Haile Ambaye ; Valeria Lauter; From x-ray telescopes to neutron focusing. Proc. SPIE 8147, Optics for EUV, X-Ray, and Gamma-Ray Astronomy V, 81470B (September 30, 2011); doi:10.1117/12.897325.

Spinoff Application: Radionuclide imaging

MEDICAL IMAGING

- Animal imaging technology important for biomedical science

  E.g., therapeutic development, disease study

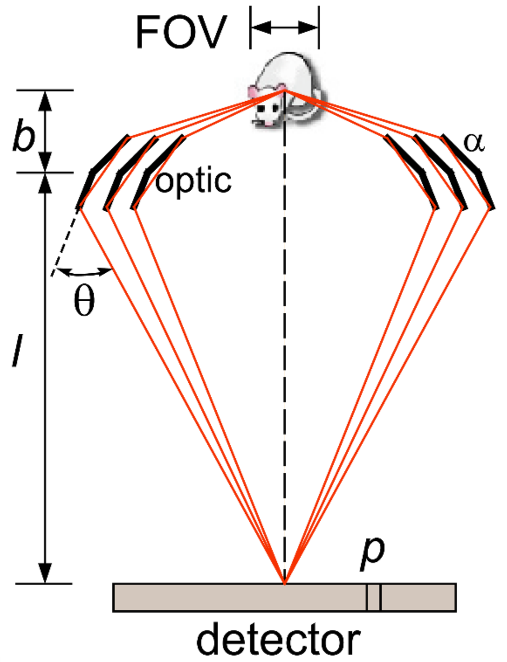
- Non-invasive imaging plays a crucial role in anatomical studies

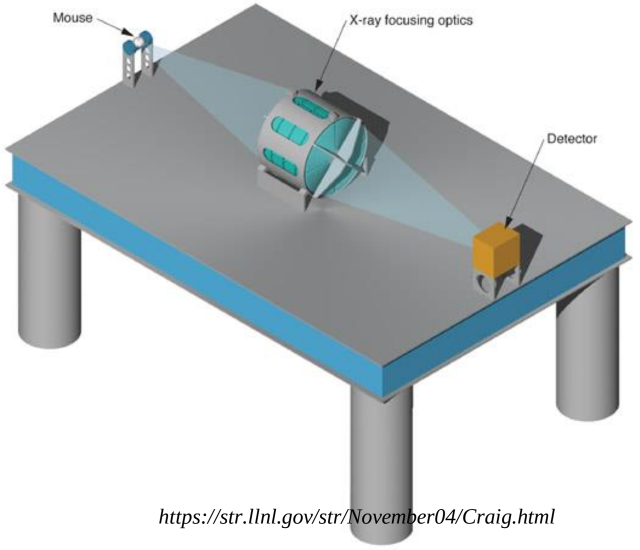
  Ultrasound: ~200 μm resolution

  CT & MRI: 25–50 μm resolution

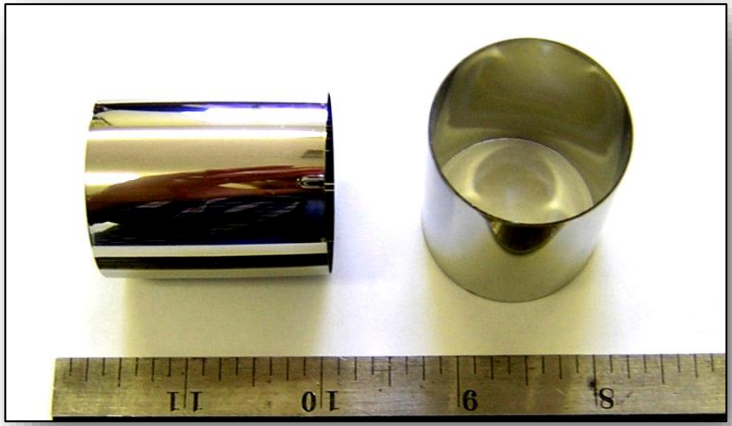
  Functional & Metabolic studies

  SPECT & PET: ~1 mm resolution





https://str.llnl.gov/str/November04/Craig.html



https://e-reports-ext.llnl.gov/pdf/305422.pdf

Ongoing Improvements

- Typical resolutions are ~ 25 arcsec HPD and ~4-10 arcsec FWHM for our production optics.
- Efforts underway to improve the resolution include:
- Better quality mandrels - Lower-stress electroforming
- Direct fabrication (& polishing)
- Post fabrication figure correction
- More precise alignment and assembly
- The near-term goal of this work is a few arcsec HEW and arcsec-level FWHM.

Improved Mandrels: Zeeko Polishing Machine

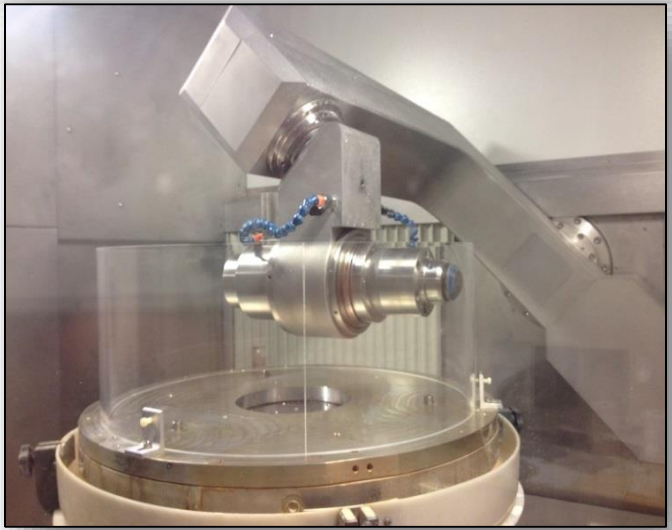
- The machine utilizes a “bonnet” technique in which an inflated rubber hemispherical diaphragm supports the polishing medium.

- There are different “bonnet” sizes (20 mm, 40 mm and 80 mm radii of curvature)

- This computer-controlled deterministic polishing processes leads to a high convergence rate.

- Tool path generation (**TPG**) software had to be developed.

- Direct-fabrication of X-ray mirror



Improved Mandrels: Zeeko Polishing Machine

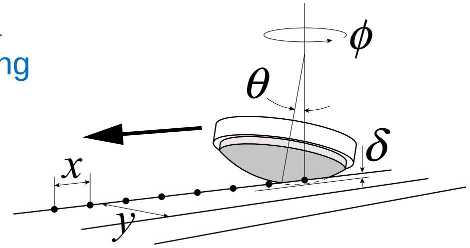
Parametric wear pattern simulation enables a more efficient method of exploring the polishing parameter space.

Wear rate is proportional to :

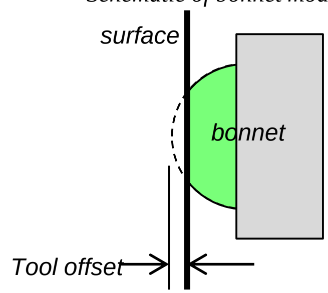
- Velocity of bonnet depends on
  - Spindle rotation
  - Head attack angles
- Bonnet pressure depends on
  - Internal pressure of bonnet
  - Bonnet structural and mechanical properties

Parameter optimization

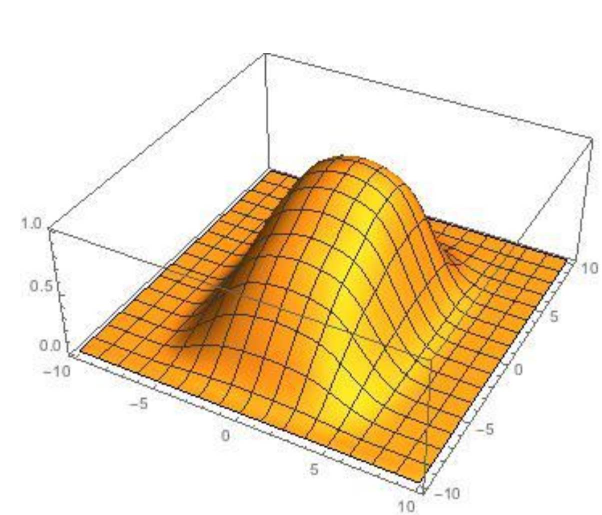
Bonnet pressure
Spindle speed
Tool Offset



Schematic of bonnet model

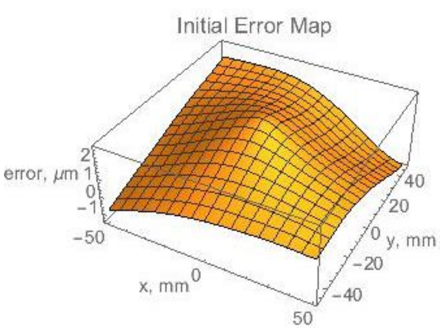


Measured wear function



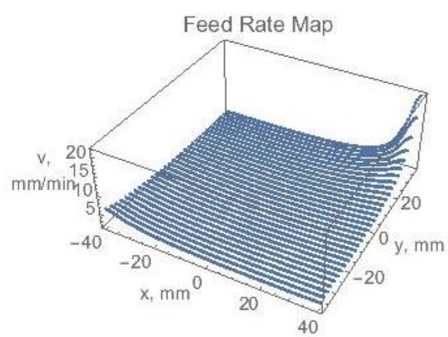
Wear function characterization

Richardson-Lucy deconvolution algorithm + small nonlinear correction (Tends to generate smoother edge transitions)



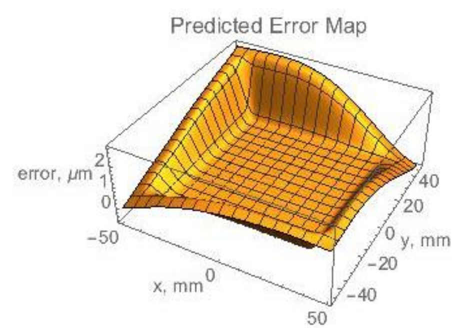
Initial error map derived from metrology data.

*RMS slope errors along x-axis are **8 arcsec**.*



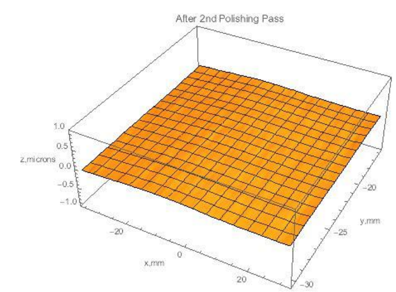
Derived feed rate map.

Feed rates range from 1.35-20 mm/min.



Predicted result of polishing iteration.

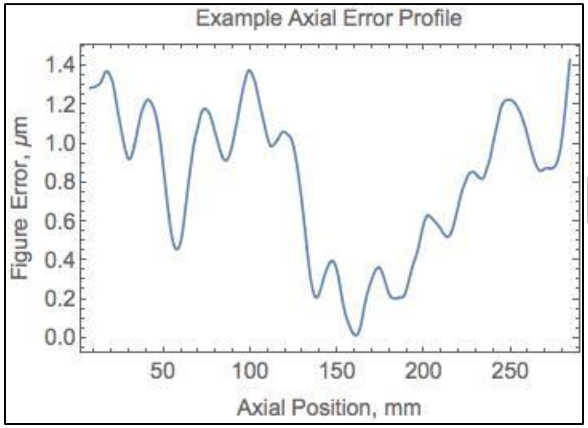
*Predicted RMS slope errors are **0.6 arcsec***

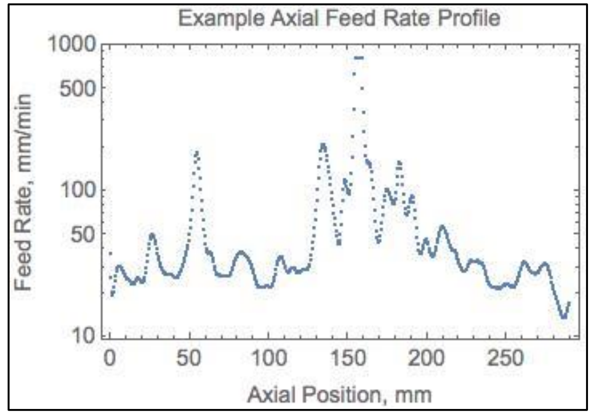


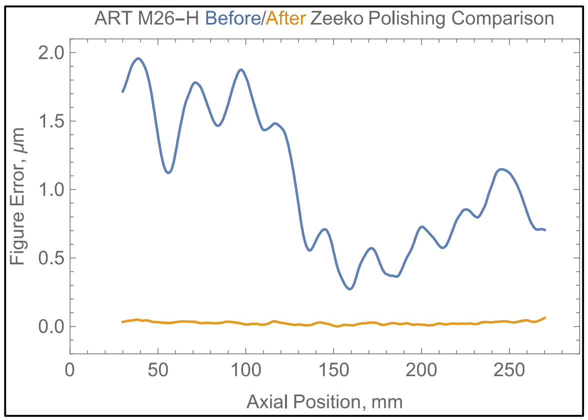
Error map derived from metrology data.

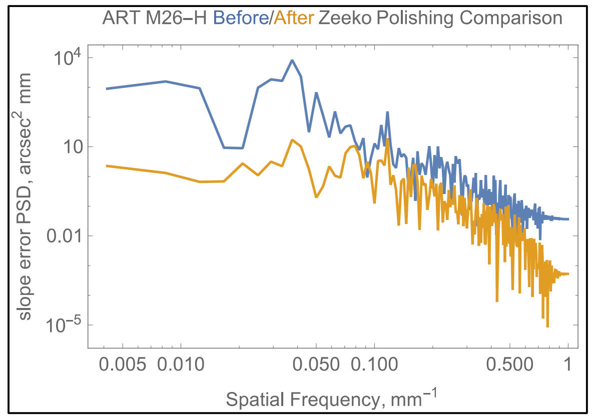
*RMS slope errors were reduced to **0.5 arcsec***

Mandrel Demonstration









	before	after
Figure error (St. Dev.)	500 nm	10.7 nm
Slope error (> 2 cm) (RMS)	6.32 arcsec	0.30 arcsec
Low frequency (> 7 cm) slope error (RMS)	2.66 arcsec	0.09 arcsec
Mid frequency (2-7 cm) slope error (RMS)	5.73 arcsec	0.29 arcsec

Mandrel > 5x better than any made with conventional polishing

Lower electroforming stresses: Pulsed Plating

- Reduce stress variations in electroforming through pulsed plating.

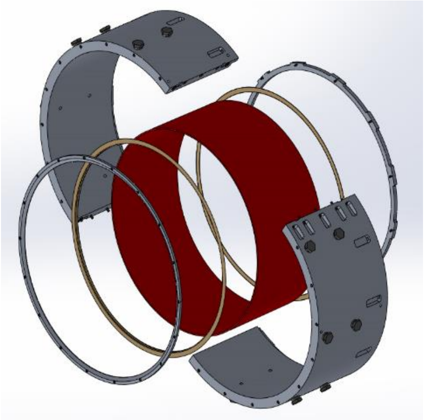
  - Periodic reversal of polarity\during electroforming alternates deposition with selective etching, providing a finer grain structure and denser packing.
  - Recent evidence shows that the shells plated this way are very low stress and closer to the mandrel shape than with conventional electroforming.

- Circularity is key for a good FWHM - Pulsed plating of pure nickel recently demonstrated the micron-level circularity necessary for arc-second-level FWHM resolution.

Full-shell direct fabrication

- Development of the technology to figure and polish thin x-ray metal optics directly
- Finite-Element Analysis shows that full-shell mirrors with thickness ~ 1.5 mm will be stable enough to be polished directly and robust enough to be handled
- Metal substrates - to improve the mechanical stability, and to reduce the manufacturing costs
  - Single-point diamond turning instead of grinding process
- Utilization of computer controlled deterministic polishing, quick convergence to the desired surface figure.

Backing support system - A thin layer of backing material (not shown) acts as an interface between the mirror shell (red) and the stiff outer support clam-shell (gray).



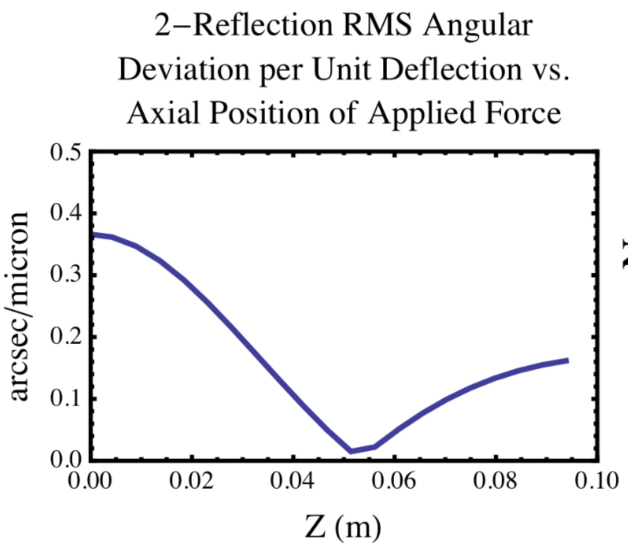
- In situ metrology system - phase-measuring deflectometry (PMD).
  - a perfect fringe pattern displayed by a monitor is observed by a camera after refection from the surface under the test.
  - Deviations from perfect spacing of the observed fringe pattern measured at multiple phases provides an unambiguous measurement of deviations in the slope of the mirror surface from its ideal shape.
- newly developed fixtures to provide uniform back support to the entire shell during figuring and polishing.
  - stiff outer shell and a thin layer of backing/interface material that goes between the mirror shell and the outer support.
    - high-viscosity liquids
    - Pitch
    - granular materials - spherical glass beads

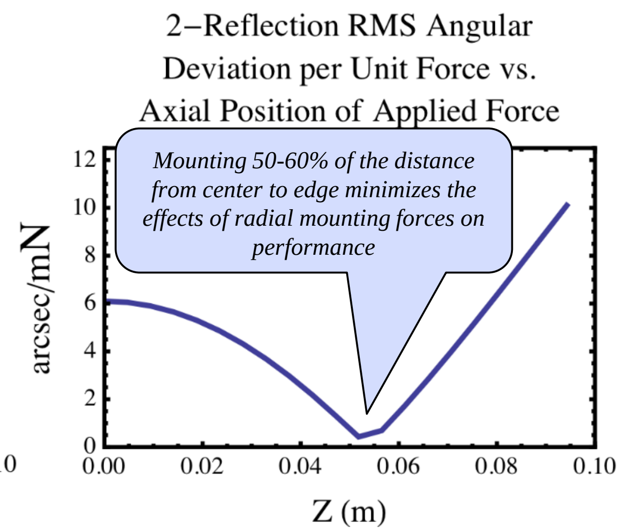
*M. Gubarev ; B. Ramsey ; J. K. Kolodziejczak ; W. S. Smith ; J. Roche ; W. Jones ; C. Griffith ; T. Kester ; C. Atkins ; W. Arnold;
Direct fabrication of full-shell x-ray optics . Proc. SPIE 9603, Optics for EUV, X-Ray, and Gamma-Ray Astronomy VII, 96030V (September 4, 2015); doi:10.1117/12.2190020.*

Mounting optimization

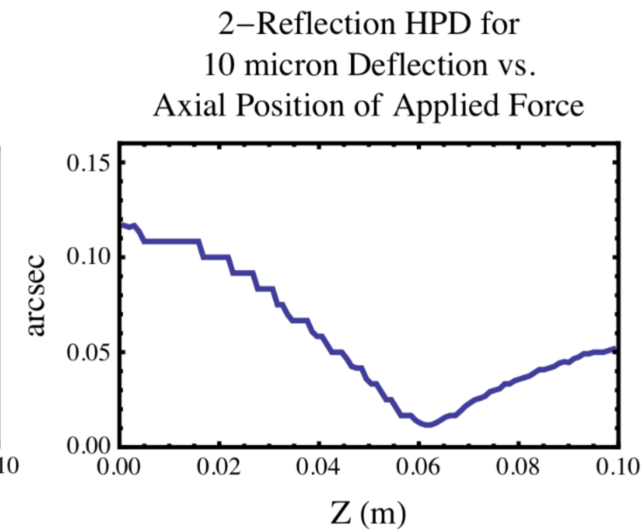
Performance vs. Axial Mounting Location

- The performance analysis of the cylindrical shell was performed, using both analytical methods and finite element analysis (FEA).
- Analytical methods were applied in Mathematica® and detailed finite element models (FEMs) were made in ANSYS.





Analytical models

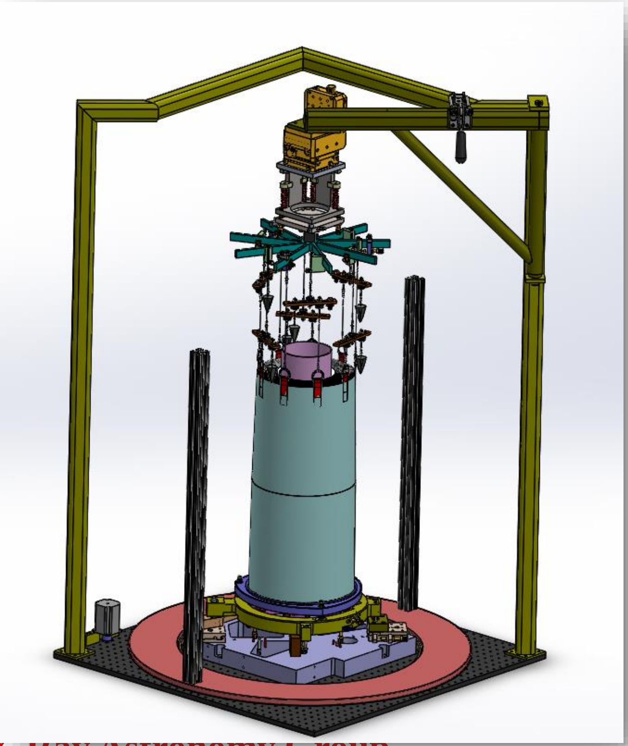


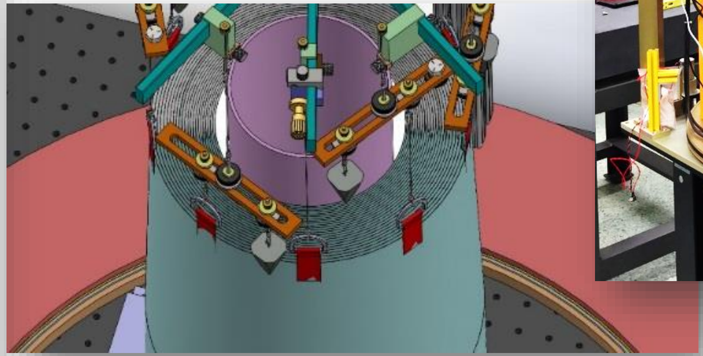
FEA simulations

Jacqueline M. Roche ; Jeffery J. Kolodziejczak ; Stephen L. O'Dell ; Ronald F. Elsner ; Martin C. Weisskopf ; Brian Ramsey ; Mikhail V. Gubarev; Opto-mechanical analyses for performance optimization of lightweight grazing-incidence mirrors . Proc. SPIE 8861, Optics for EUV, X-Ray, and Gamma-Ray Astronomy VI, 88611G (September 26, 2013); doi:10.1117/12.2026884.

Alignment

- Strings approach – mirror is hung with strings
- Equalizing the strings tension – self leveling and minimum distortions





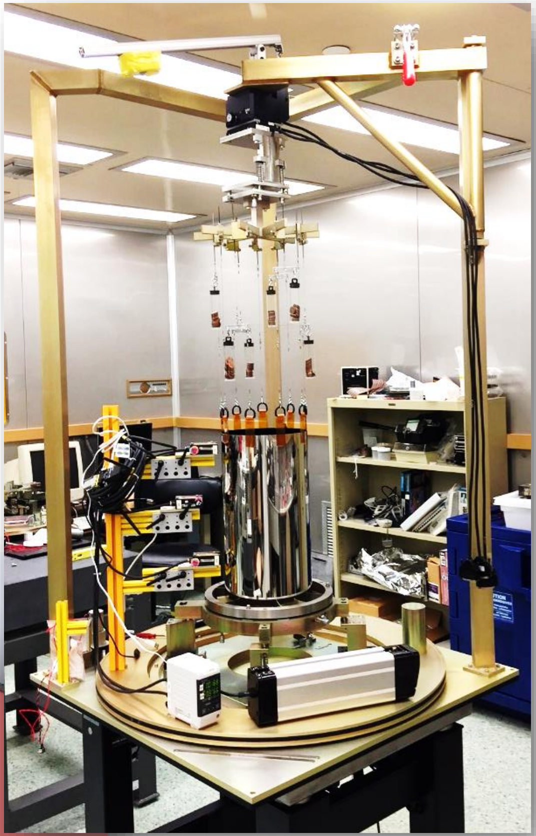


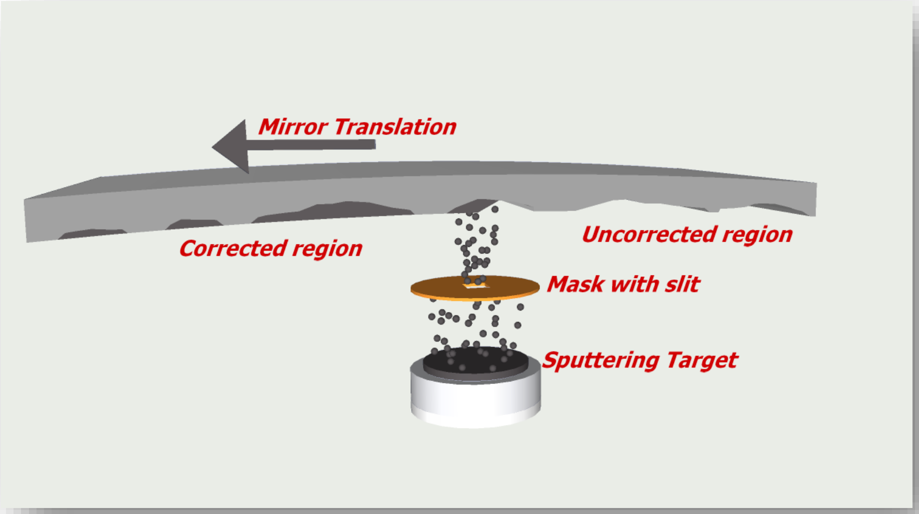
Figure Correction: Differential Deposition

What Differential deposition is a technique for correcting figure errors in optics

How Use physical vapor deposition to selectively deposit material on the mirror surface to smooth out figure imperfections

Why

- Can be used on **any type** of optic, full-shell or segmented, mounted or unmounted
- Can be used to correct a wide range of spatial errors. Could be used in conjunction with other techniques… e.g. active optics.



Surface profile metrology

↓

Develop correction profile "Hitmap"

↓

Simulations – translation velocity of shell

↓

Differential deposition

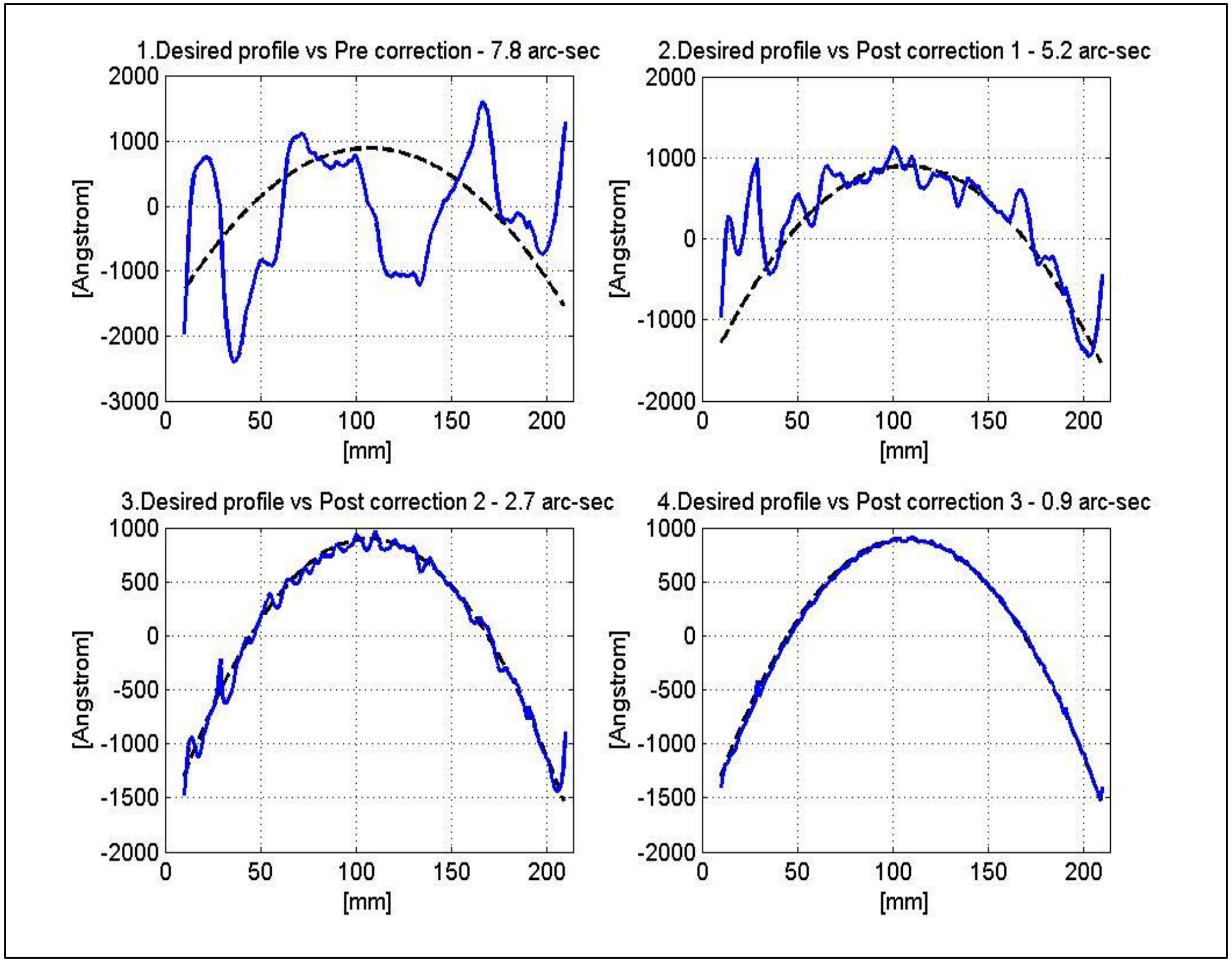
↓

Surface profile metrology

↓

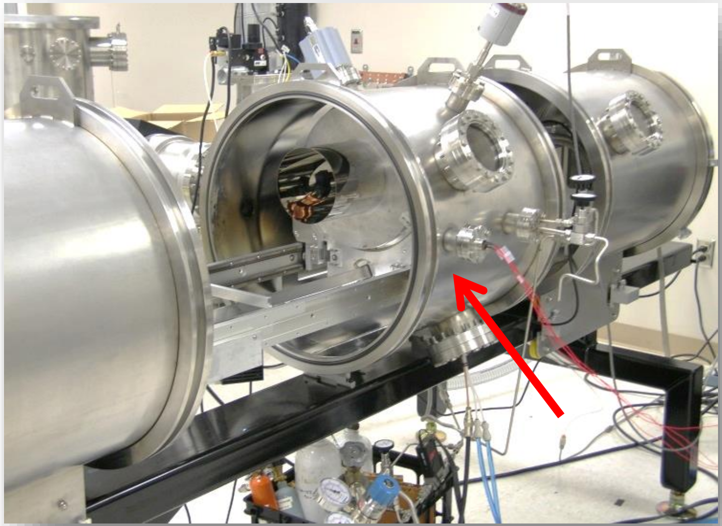
X-ray testing

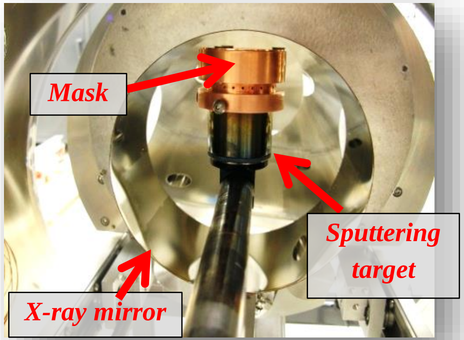
Process Sequence – Differential Deposition



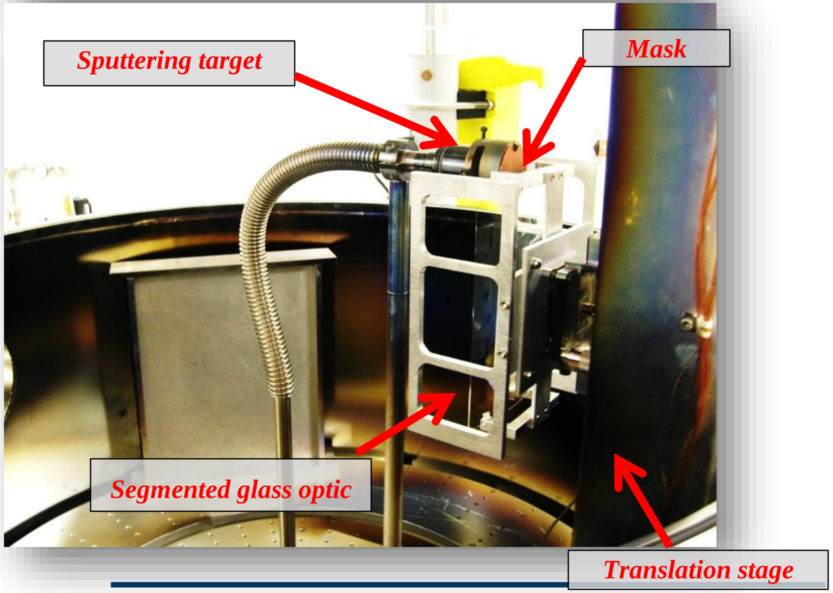
Simulated correction sequence showing parabolic axial figure profile before (top left) and after 3 stages of correction using a beam of FWHM = 14mm, 5.2 mm and 1.7 mm respectively. The dotted line gives the desired figure and the solid line gives the figure obtained at each stage. Overall, resolution improved from 7.8 arcsec to 0.9 arcsec HEW (2 bounce equivalent).

Coating systems

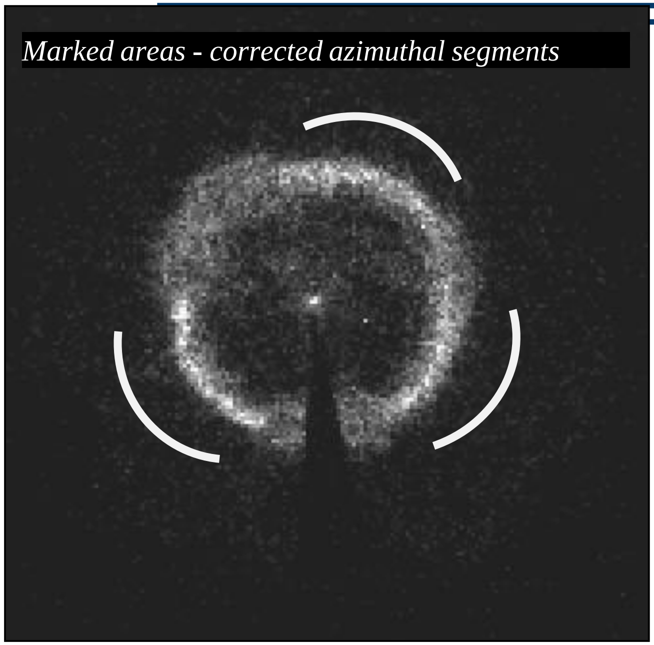


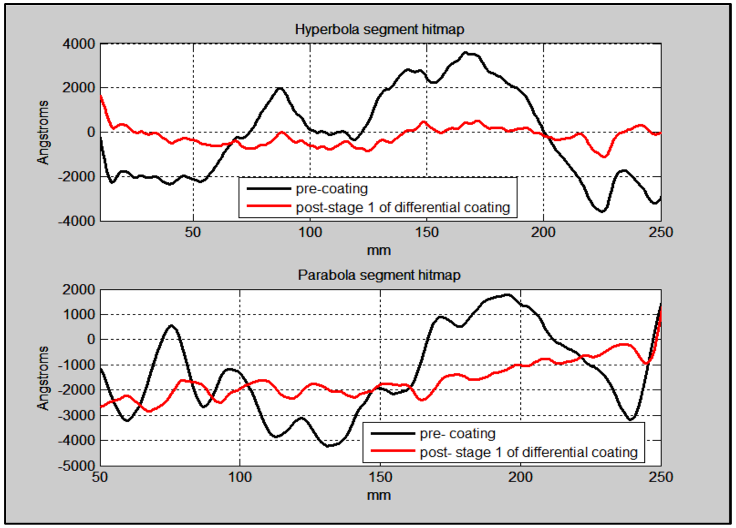


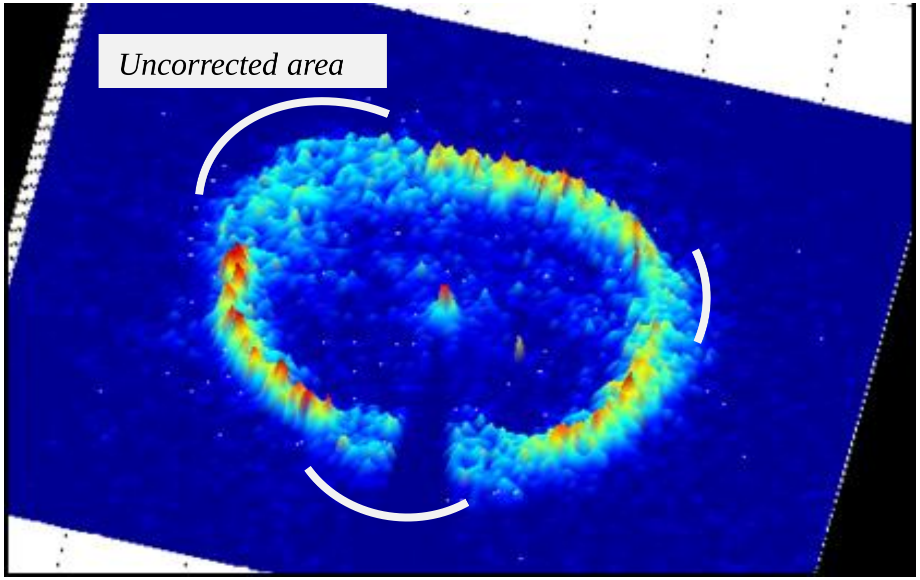
Sputtering head with copper mask positioned inside shell



X-ray testing – pre-and post- differential coating



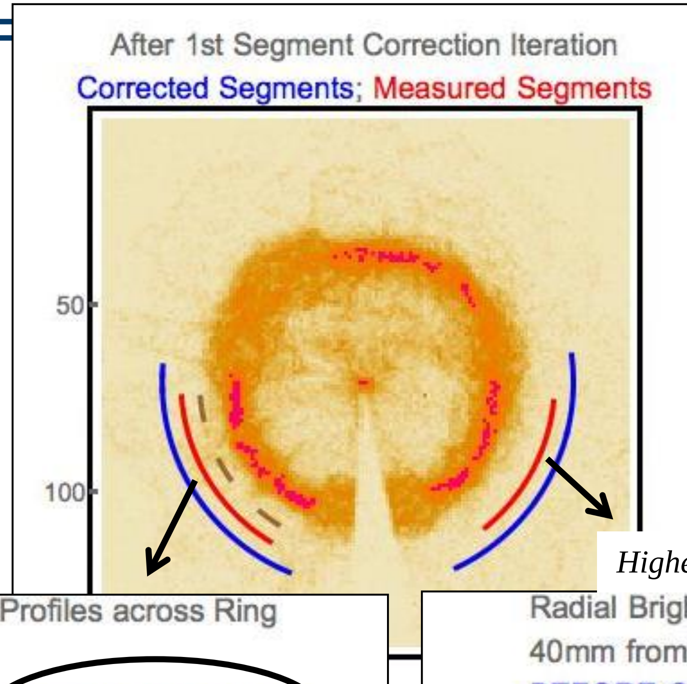




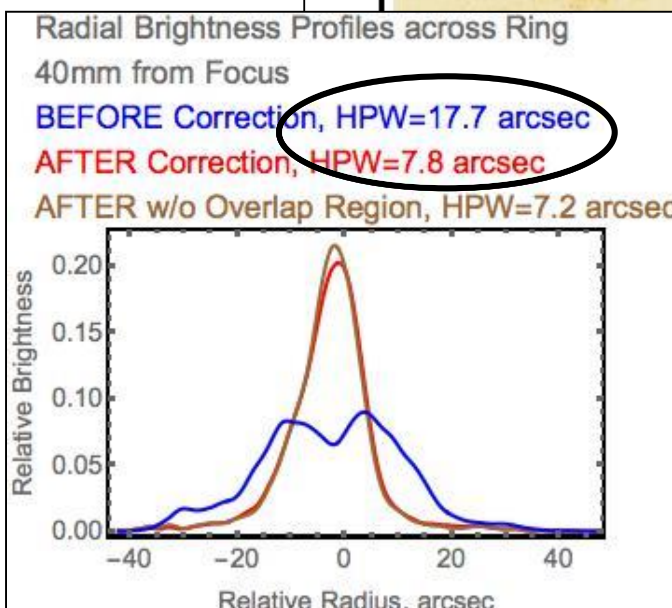
- Plots shows intra-focus X-ray image (-40 mm) of the corrected shell
- Corrected segments are visually obvious compared to the uncorrected in X-ray testing with the CCD

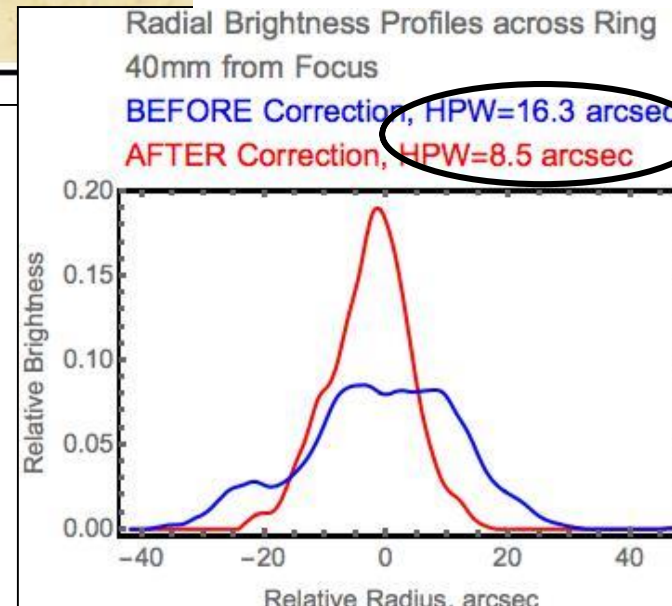
X-ray testing – pre-and post- differential coating

A factor of >2 improvement is achieved with one stage of correction



Higher frequency- correction





Conclusion

- Full-shell optics –
  - Integrated P and H segments
  - Full-circles of revolution
  - Inherently stable
  - Better alignment and assembly
  - Less stress effects due to coatings
- At MSFC
  - Electroform nickel replication has been used for past 20 years and efforts are underway to improve the optics resolution
  - Full-shell direct fabrication using robotic polishing machines are under investigation